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Computational modelling of random distribution of stresses for wooden structures

Численное моделирование случайного распределения напряжений для деревянных конструкций

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Key words: restoration; wooden structures; Monte Carlo simulation; timber; probabilistic analysis

Ключевые слова: реставрация; деревянные конструкции; метод Монте-Карло; вероятностный анализ

Abstract. Stochastic allocation is the main characteristic of processes which can be described in wooden structures. Random distribution of stresses and deformations in such structures is mostly based on timber imperfections, such as different curvature of sticks, presence of knots, twigs and gnarls. Due to restoration works using of test methods and experiments in wooden structures, especially in architectural monuments, is limited because of high labor contribution and restrictions for protection of historic cultural heritage. Therefore, for decreasing efforts application of statistical methods with help of software tools is necessary and highly important in case of restoration of wooden structures. In particular, this article describes solution of design problem in choosing the optimal step of wall dowels with help of Monte Carlo method by the time of restoration in the Church of the Transfiguration on Kizhi Island. For analysis of stresses in cribbed panel wall an analytical model, which describes structural behavior sticks and dowels according to all imperfections, with three different dowels steps (0.67 m, 1.0 m and 1.67 m) was created in SCAD software. Stick curvature has been changed longitudinal direction and after that calculation of stresses was performed. As the result the most optimal dowel step is one meter, such as it produces minimal stresses due to the minimum intervention in the structure.

Аннотация. Вероятностное распределение является основной характеристикой процессов, которые могут быть описаны в деревянных конструкций. Случайное распределение напряжений и деформаций в таких конструкциях основывается на присутствии дефектов древесины, таких как различие кривизны брусков, узлы, ветки и свилеватость. Реставрационные работы с использованием экспериментальных методов, особенно в архитектурных памятниках, ограничены из-за трудозатратности и правил охраны исторического культурного наследия. Поэтому при восстановлении деревянных конструкций необходимо применение статистических методов и программных средств. Целью данного исследования является обоснование нового способа проектирования в ходе реконструкции сооружений, зависящих от вероятностных факторов, путем введения метода Монте-Карло в процедуру моделирования методом конечных элементов.В частности, в данной статье описывается выбор оптимального шага стеновых дюбелей с помощью метода Монте-Карло во время реставрации в церкви Преображения Господня на острове Кижи. Для анализа напряжений панельной стены в программе SCAD была создана аналитическая модель, которая описывает поведение брусков и дюбелей в соответствии со всеми несовершенствами, с тремя различными шагами нагелей (0,67 м., 1,0 м и 1,67 м). Изгиб брусков изменяли в продольном направлении, после чего проводили расчет напряжений. Было выявлено, что самый оптимальный шаг дюбелей – один метр, так как он вызывает наименьшие напряжения

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при минимальном вмешательстве в конструкцию. Результаты были сравнены с законом непрерывного распределения и законом распределения Гаусса. Таким образом, была разработана новая методика для решения конструктивных задач методом Монте Карло и доказана ее корректность.

Introduction

Historically, timber is the most wide spread material in most of the countries for different types of structures, such as residentional houses, household buildings and even temples or castles (for example, Buddhist temple Hōryū-ji in Nara, Japan). The main reasons of such common timber usage are relatively simple processing of materials and, of course, a high accessibility timber from woods. In comparison with concrete structures, lifetime of the timber is not very high; therefore wooden structures are not durable. That is why survived until present days from last centuries wooden structures can be estimated as architectural monuments and considering this part of the cultural heritage is of outstanding interest and therefore need to be preserved as part of the world heritage of mankind as a whole.

Problem of restoration of architectural monuments, especially churches and temples, is one of the most significant around the world. It belongs not only to the Central Europe [1, 2] but also to Southeast Asia [3], South America [4] and East Asia [5]. In Russian Federation the most famous and significant historical complex of wooden structures is a national open-air museum Kizhi Pogost which consists of more than 80 historical wooden structures and belongs to UNESCO World Heritage site. Since 1980th the Church of the Transfiguration which is the central architectural object in this ensemble is under restoration processes [6]. Nowadays a lot of structural zones are restored and it’s required to pick up the most optimal scheme of dowel bars planting zones and their number. It is important for the complete enforcing of a middle quadrangle located at the top of the octagon. For this purpose it is supposed to perform the natural experiment but such kind of tests are restricted from the point of view conservation the structure as much as possible. Moreover, it is very wasteful and requires a lot of efforts [7].

Worldwide experience provides different kinds of solutions for problem of safety restoration works. For example, non-destructive techniques enable conduct an inspection of wooden structures of protected buildings without affection disturbances of structures. Such non-destructive techniques as ultrasound and thermography are used in inspections of the wooden roofs of buildings to identify dampness, deterioration, density loss and defects as a means of assessing their conservation status. Thermography identifies different materials and moisture content while ultrasound detects the various degrees of deterioration and density-loss in areas of the wood with high moisture content [8]. According to non-destructive inspection of the Church of the Transfiguration it was found out that the walls of the main octagon are not stiff enough and should be bound by rigid connections (dowels) for prevention of buckling in the vertical direction. Choosing of the number and step of such dowels is the main purpose of this research and highly important for continuation of restoration works. Additionally to difficulties of natural experiment that were mentioned above restoration of architectural monuments is complicated because of the difficulties in restoration site. Cultural monuments should not be closed for visitors for a long period from the financial point of view [9]. The same procedure is now going on the restoration site of the Church of the Transfiguration what makes restoration process more complicated.

Implementation of modern methods of simulation and modelling in vast number of cases allows to come up with the solution of engineering problems without conducting any experiments. For example, BIM technologies may represent the three-dimensional compounds of the building [10] and the several phases of restoration work in a fixed schedule [11]. And in order to predict the structural damage and deformed configuration of the building under the loading it is reasonable to use FEM modelling as the most convenient and accurate.

However, in case of restoration engineers should work with probability factors, which cannot be considered by software for simulation because of the vast number of information. For the studied wall from the Church of the Transfiguration which was mentioned above it is impossible to simulate behavior of every timber beam because of the different curvature of every part and different stiffness characteristic of every trunk. The most appropriate way to consider the contribution of every trunk in the work of a whole structure is usage of probabilistic methods. One of the most usable probabilistic methods in engineering is a Monte-Carlo method. It is known that Monte Carlo simulation can be used for evaluation of efficiency, reliability and capacity of different models [12]. Monte-Carlo simulation is already applied for evaluation of restoration costs [13], seismic reliability assessment of classical columns [14], production assurance analyses in subsea production system [15]. This method helps to consider corrosion damaging [16] and develop strategies for the restoration of structure [17]. But application of Monte Carlo simulation for choosing the geometry of structure for improving stiffness is not so widely used as it should be though it allows changing the geometry without any natural experiments, disturbance of restored building and high efforts [18]. Moreover, Monte Carlo simulation is successfully used for analysis of wooden structures, such as glued timber roofs [19] and bolted timber joints [20]. Therefore, Monte Carlo simulation in collaboration with FEM truss system should be used for modelling of the structure of a middle quadrangle located at the top of the octagon and choosing of the optimal number and step of dowels for its enforcing.

Taking the foregoing into consideration, let us formulate the purpose and objectives of the research.

The purpose of this study is substantiation of the new method for structural design during renovation of systems which depend on probabilistic factors by introducing Monte Carlo simulation in finite element modelling procedure. The Church of the Transfiguration should be used as an example for design task with octagon walls which is described in the next section.

It can be done by achieving the following objectives:

1. Modelling of the system with conditional dowels and equivalent stiffness;

2. FEM simulation of probabilistic factors for every design scheme;

3. Deriving of characteristics for Monte Carlo simulation;

4. Reliability evaluation of performed numerical experiments by comparison with normal probability law and by the law of the uniform density

5. Choosing the most rational and efficient design scheme of dowels for further modernization of the octagon walls.

Methods

The Church of the Transfiguration was built in 1714. It consists of the one main octagon in which four walls are connected with the earth and the res four walls are suspension. This octagon bears loads from a whole structure as main support for 22 different domes and two smaller octagons. This building is unique because it does not have any nails. Nowadays it has following deformations [21]:

- displacements of a primary tilt are from 15 to 30 cm because of the differential settlement;
- displacements of a secondary tilt are from 32 to 36 cm because of the deformation in the main octagon;
- main octagon is inclined for 35 cm in the north direction and for 55 cm in the east direction;
- local buckling of the walls of the main octagon is up to 35 cm;
- deflections in beams achieve 16 cm.

Such high deformations show that the local and global stiffness of the structure and its separate parts (trunks) is not sufficient. It can be a consequence of very various reasons. First is a weak bond of trunks in the horizontal direction and the absence of dowels in a longitudinal direction. Second reason is an accumulation of deformation due to the impact of temporary loads throughout a long time period. The next reason is the humidity difference of inside and outsides layers of the walls. Due to the swelling of outsides layers trunks bend out. Finally, seasonal temperature changes cause uneven heating of inside and outside surfaces what also increases deflections of trunks due to the time.

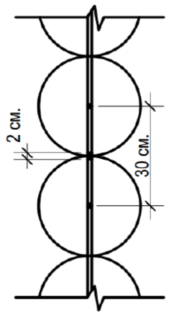

Figure 1. Fragmant of installation of dowels in the trunks for determination of the length of functional part

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In order to increase stiffness of the octagon in a horizontal direction it is necessary to put some dowels along a whole wall. Such vertical bonds will prevent any buckling of trunks. But it is necessary to take into account all impacts which cause deformations and, moreover, most of imperfections of timber and trunks' geometry should be considered.

Solution of such problem was derived by Monte Carlo simulation. The basis of the design scheme is an east diagonal wall of the main octagon. Its trunks have diameter from 20 to 30 cm. Curvature along the trunk is also various (3–5 cm). The length of the wall is 6 meters. There are also imperfections such as knots, twigs and gnarls.

Following assumptions have been applied:

- the log panel consists of 7 trunks with length 5 meters and diameter 30 cm;
- loads act only in vertical direction;
- step of dowels should be no more than 2 m and no less than 0.5 m;
- according to [22] for such step of dowels the diameter of every dowel was prescribed as 2.4 cm;
- horizontal and vertical trunks are modelled as trusses with a reduced cross sections;
- in the spans trunks are supported on each other in n points. This points are the places of dowels installation;
- dowels are modelled by vertical trusses;
- system deformability is based on dowel bendings.

In order to model dowels correctly the reduced cross section of dowels was calculated. Diameter of dowel $D =$ 2.4 cm. Mostly it is rigidly fixed but in the central part (effective part) it works on a slice and a bend. The length of this central part depends on the gap between of trunks, the height of the shear zone, the grade of wood ant etc. The conditional length was assigned by Figure1. Stiffness of the dowel with the length 30 cm is not the same for dowel with the length of 2 cm, that is why for design scheme conditional values of stiffness (equivalent stiffness) were used instead of real values.

Schema A **Schema B**

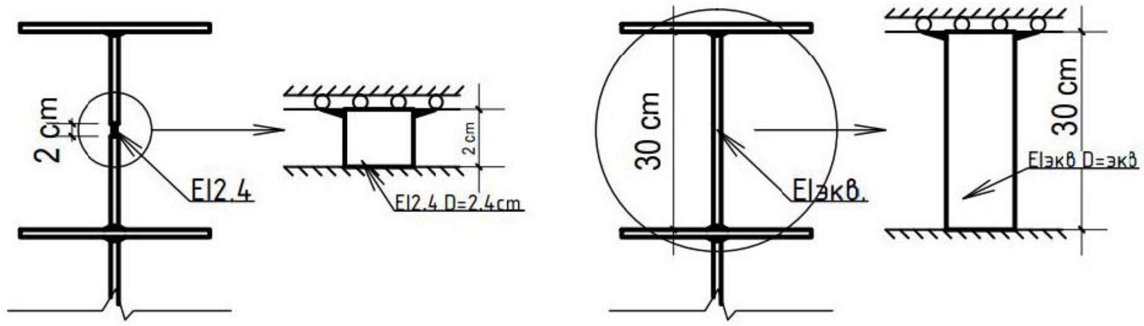

Figure 2. Schemes of equivalent stiffness

Stiffness of conditional dowel δ_{eq} should be larger than stiffness of the real dowel $\delta_{2,4}$. This difference is proportional to the relation of their lengths to the third power:

$$\delta_{eq} = \frac{l_{eq}^3}{3EJ_{eq}}; \quad \delta_{2,4} = \frac{l_{2,4}^3}{3EJ_{2,4}} \quad and \quad \delta_{eq} = \delta_{2,4}, \tag{1}$$

where $l_{2,4} = 2cm$ and $l_{eq} = 30cm$ are the length of effective part of the dowel and the length of the equivalent dowel respectively; $E = 100000\ kg/cm$ is an elasticity modulus; J_{eq} and $J_{2,4}$ are the moments of inertia of effective part of the dowel and the equivalent dowel respectively. Moment of inertia for effective part of the dowel can be calculated through the dimeter:

$$J_{2,4} = 0.05D^4 = 0.05 \cdot 2.4^4 = 1.66\ cm^4 \tag{2}$$

Therefore, from Eq. (1) J_{eq} can be derived:

$$J_{eq} = \frac{l_{eq}^3 \cdot 3EJ_{2,4}}{3El_{2.4}^3} = \frac{l_{eq}^3 \cdot J_{2,4}}{l_{2.4}^3} = \frac{30^3 \cdot 1.66}{2^3} = 5602 \ cm^4 \quad (3)$$

Diameter of equivalent dowel can be calculated from Equation (2):

$$D_{eq} = \sqrt[4]{\frac{J_{eq}}{0.05}} = \sqrt[4]{\frac{5602}{0.05}} = 18 \ cm \quad (4)$$

For modeling of design scheme FEM tools were used. Design scheme was simulated as a truss model in the SCAD software for three different steps of dowels (1 m, 1.67 m and 0.71 m), which are represented in Figures 3, 4 and 5 respectively. Stiffness for truss elements were modelled by means of numerical descriptions: EF is a longitudinal stiffness, where $F = \pi D^2/4$ is the area of element; $EI_z = EI_y$ is a bending stiffness, where $I_z = I_y = \pi D^4/64$ are the moments of inertia; GI_k is a torsional stiffness, where $G = E/2(1+\mu)$ and $I_k = \pi D^4/32$; $GF_y = GF_z$ is a shear stiffness. All these characteristics for logs, dowels and the cuttings (bonds) were calculated and provided in Table 1, where numbers in brackets (*) are the number of stiffness types. It should be also noticed, that truss element for cuttings are modelled as trusses in three dimensional space with infinite stiffness.

Applied loads were derived from corresponding projects and reports of LLC “DCF “Stroyrekonstruktsiya”. Since overall load for 7 trunk of the main octagon is approximately equal $9.8 \ kN$ output internal forces for dowels are very small (third order values). Such as the main task is to choose step of dowels conditional load ($98 \ kN$) was prescribed. This assumption enables to evaluate probabilistic characteristics not as thousandths but as decimal values.

Table 1. Calculated parameters for simulation of element stiffness

	Log	Dowel	Cutting
$EF, \ [kN]$	692370	249253	98000000
$EI_z = EI_y$, $[kN \cdot m^2]$	3894.52	548.99	3894.52
GI_k, $[kN \cdot m^2]$	2614.64	341.04	-
$GF_y = GF_z, \ [kN]$	233877	84197	233877

After modelling of every case in SCAD software for every design model the calculations without prescribed displacements in Y-direction were produced. After that according to Monte Carlo method in every design model trunks curvature was changed in longitudinal direction. Calculations were produced after every modification and the dowel with maximal internal force was registered. Consistently, curvatures of other dowels were changed up to the moment when selection became representative. For solution of this problem overall 99 calculations were performed for every design scheme.

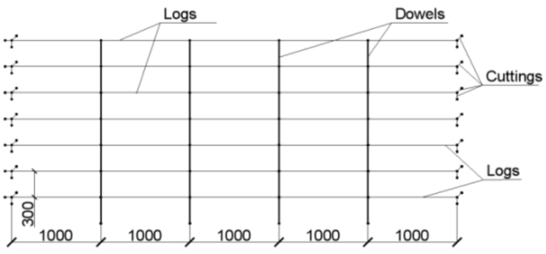

Figure 3. Design scheme for step of dowels 1 m

Figure 4. Design scheme for 1.67 m

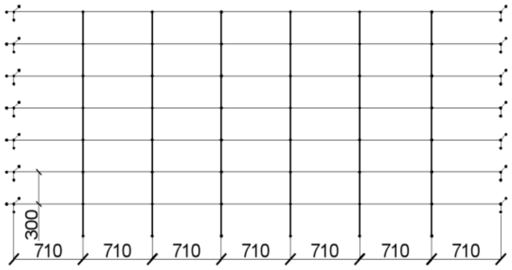

Figure 5. Design scheme for step of dowels 0.71 m

Results and Discussion

By derived above values tables with completed ranking were created for every design scheme. For the step of dowels 1 m maxim value of random variables (internal forces in dowels) $x_{i\min} = 1.7$ and the maximum value $x_{i\max} = 9.08$. For the step 1.67 m these values were equal 1.86 and 16.25 respectively. And for the step of dowels 0.71 m random variables took the values from $x_{i\min} = 0.57$ to $x_{i\max} = 9.08$ In Table 2 maximum and minimum values of random variables (internal forces in dowels) are provided. After that all range of variables was divided into intervals (J_i) and by the frequency of occurrence (m_i) corresponding probability of the emergence of a random variable (p_i^*) was calculated. Then histograms of the distribution were created and provided in Figures 6, 7 and 8.

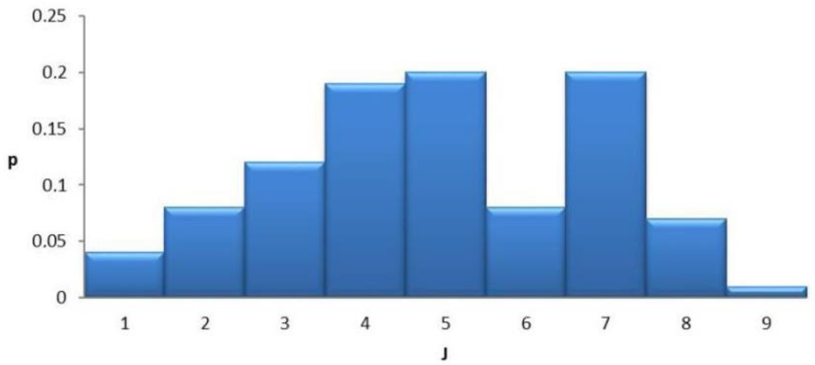

Figure 6. Histogram of the distribution for step of dowels 1 m (9 intervals)

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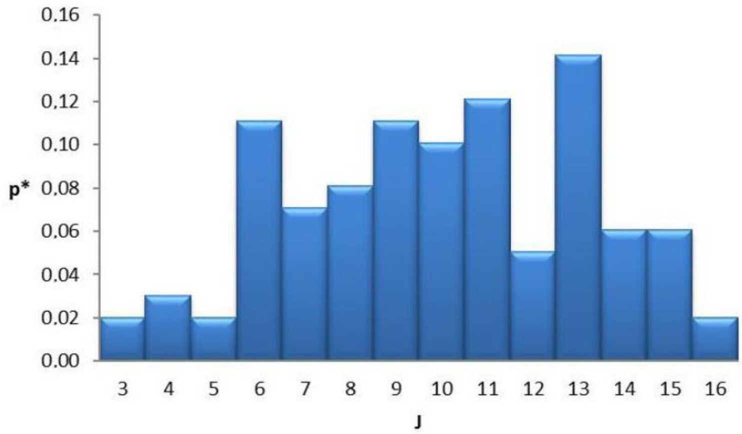

Figure 7. Histogram of the distribution for step of dowels 1.67 m (14 intervals)

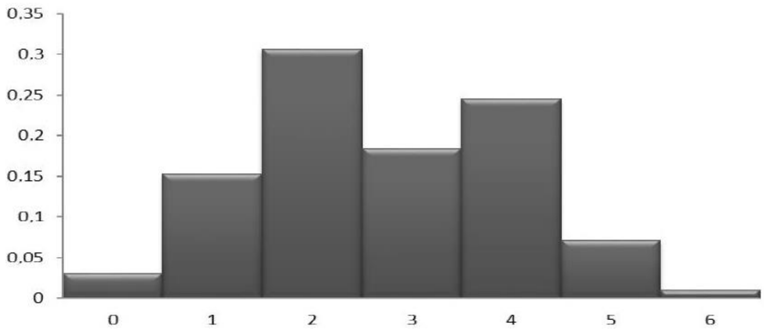

Figure 8. Histogram of the distribution for step of dowels 0.71 m (6 intervals)

For complete analysis of this discrete distribution such numerical characteristics as the statistical average value $(\overline{x_n})$, the standard deviation (σ_n), dispersion (D) and the coefficient of variation (COV) were calculated [23]. For comparison with recent researches reliability indexes β according to first order reliability method (FORM) were calculated [24].

Calculated numerical characteristics are provided in the Table 2.

Table 2. Numerical characteristics of the discrete distribution variables for different steps of dowels

Characteristics	**Step of dowels**		
	1 m	1.67 m	0.71 m
Number of tests	99	99	99
$\overline{x_n}$	5.415	10.43	3.18
σ_n	1.87	3.21	1.29
D	3.506	10.33	1.67
COV	0.345	0.307	0.406
β	2.896	3.249	2.465

Alignment of the statistical series was held by the normal probability law and by the law of the uniform density. The law of the normal probability is:

$$f(x) = \frac{1}{\sigma_n \cdot \sqrt{2\pi}} \cdot e^{\frac{1}{2}\left(\frac{x_i - \bar{x}^2}{\sigma_n}\right)^2}, \quad (5)$$

where σ_n is a standard deviation; x_i are numerical values of the random variable X and $\bar{x}$ is a statistical average value. And the law of the uniform density has a following form:

$$f(x) = \frac{(J_{i+1} - J_i)}{\overline{\Delta J}} p_i^*. \quad (6)$$

For verification of the distribution laws Person criteria were applied. For this purposes distribution curve was combined with every histogram and the measure of divergence was calculated with help of the following formula:

$$\chi^2 = \sum_{i=1}^{n} \frac{(m_i - np_i)^2}{np_i}, \quad (7)$$

where χ^2 is the criterion of consent; m_i is a measure of occurrence; p_i is the corresponding probability of occurrence and n is the number of tests. Then number of degrees of freedom (r) was calculated as a difference between the number of bits (k) and the number of imposed bonds (s). After that by Table 4 probability (p) was found. If the value of p is very small applied hypothesis is considered as implausible. If the value of p is very large the hypothesis should be considered as not contradicting to test data. The question is how small should be probability p for reconsideration of the hypothesis is quite undefined as soon as the question howl small should be the probability of occurrence for its impossibility [25]. Person criteria allow to appreciate reliability of applied model (hypothesis) and compare results numerically [26]. Results of performed calculations are provided in Table 3 for the law of uniform density and in Table 4 for the law of the normal probability.

Table 3. Evaluation of convergence by the law of uniform density

Characteristics	**Step of dowels**		
	1 m	1.67 m	0.71 m
$p_i = f(x)$	0.11	0.1	0.166
χ^2	37.65	9.01	45.94
k	9	14	7
s	3	3	3
r	6	11	4
Measure of convergence	0.00	0.68	0.00

Table 4. Evaluation of convergence by the law of the normal probability

Characteristics	Step of dowels		
	1 m	1.67 m	0.71 m
χ^2	14.53	16.72	45.94
k	9	14	7
s	3	3	3
r	6	11	4
Measure of convergence	0.038	0.16	0.77

In published works of other authors, the problem of finding the most appropriate design scheme with help of probabilistic theory in general and particularly a detailed comparison of dowel step for enforcing were not touched upon. Therefore, the comparison with other researches should be performed for reliability of the application Monte Carlo simulation for different engineering tasks [27]. In case with glued timber roofs [19] results provided by Monte Carlo simulation vary from results provided by Eurocodes from 6.4 % to 27.81 %. In case with bolted timber joints [20] Monte Carlo simulation was compared with experimental results and for different cases results varied from 10 % to 30 %.

In the present study results were compared with the law of uniform density distribution and with the law of normal probability. For the step of dowels 1m both laws do not provide any convergence (0 % by the law of uniform density and 3.8 % by the law of the normal probability) and more complicated theories should be applied. For the step of 1.67 m. the law of uniform density provides convergence 68 % while convergence by the law of normal probability is only 16 %. In the case when step of dowels is 0.71 m. the law of normal probability yields convergence 77 % whereas the law of uniform density does not provide any convergence (0 %). Therefore, application of Monte Carlo simulation for determination of the most appropriate design scheme provides high reliability and the range of applicability for Monte Carlo simulation can be extended.

Moreover, if we consist moderate consequences of failure and average cost for upgrading the safety level [28] the target reliability index β_t will be equal 4.2 what is larger than all reliability indexes for every design scheme. It means that possibility of failure is equal 0.27 %, 0.098 % and 0.68 % for dowel steps 1.0 m, 1.67 m and 0.71 m respectively. It means that all design schemes are safety and probabilities of failure are very small.

It means that the choice of the optimal step of dowels should be based on produced internal forces for every case, but also technical efforts (cost of construction, materials) should be taken into account. For the step of dowels 1 m. average value of internal forces is 53.07 kN and maximum value is 88.98 kN. For the step of dowels 1.67 m. average value of the internal forces is equal 102.21 kN whereas maximum value is 159.25 kN. In the last case (step of dowels is 0.71 m.) average value of the internal forces is 31.16 kN and maximum value is 60.07 kN. Obviously that the most optimal step of dowels is 1 m since it creates small internal forces as the case with step 1.67 m. and doesn't require too much material and installation efforts like the case with the step equal 0.71 m.

Conclusions

Influence of imperfections of wooden structures to the internal forces in dowels was analyzed as soon as the zones of the bonding logs and dowels. New algorithm for the simulation and choice of design scheme and structural elements which allows considering all imperfections of structure was created. For three different cases of steps of dowels (1 m., 1.67 m. and 0.71 m.) design scheme in FEM software was modelled and internal forces were calculated. According to Monte Carlo simulation discrete distribution with its main characteristics were derived. Convergence of every distribution for internal forces was estimated by Person criteria. According to resulted convergences assumption that internal forces comply to the law of the normal probability is proven. Optimal step of dowels for walls in the main octagon in the Church of the Transfiguration was calculated and equal 1 m. It provides small stresses by the time of relatively low construction efforts and cost. It was shown that Mote Carlo simulation provides high reliability not only for evaluation of strength of timber details but also for solution of structural problems and finding the most efficient one. Created calculation algorithm and recommended step of dowels will be used for restoration of the Church of the Transfiguration. Moreover, it can be applied for restoration of other wooden structures.

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